A Meta-heuristic Approach to Rail-Truck Intermodal Transportation of Hazardous Materials

M. Verma[1], V. Verter[2], N. Zufferey[3]

[1]Faculty of Business Administration, Memorial University, St. John's, Canada

[2]Desautels Faculty of Management, McGill University, Montreal, Canada

[3]HEC, University of Geneva, Geneva, Switzerland

Email: mverma@mun.ca,vedat.verter@mcgill.ca,Nicolas.zufferey-hec@unige.ch

Abstract–**The phenomenal growth of intermodal transportation over the past three decades, partly driven by the increasing demand for chemical around the world, has not been matched by a comparable level of academic activity, especially in the context of hazardous materials. In this work, we proposed a bi-objective optimization model and a tabu-search based solution methodology to plan rail-truck intermodal transportation of hazardous materials (hazmat). The framework was applied to solve realistic size problem instances, which were analyzed to gain managerial insights, to identify non-dominated elements of the risk-cost frontier, and to provide building blocks to develop public policy instruments**.

Index Terms –**intermodal transportation, dangerous goods, tabu-search.**

I. Introduction

Intermodality, a system of interconnected networks involving combinations of transportation modes, ensures seamless and efficient freight movement. Rail-truck intermodal transportation (IM) – involving rail-haul operation by intermodal trains, and drayage by trucks – has experienced phenomenal growth since 1980. The attractiveness of such combination primarily stems from two reasons: first, reduction in uncertainty and lead-times because of a significant portion of the transport distance is covered by intermodal trains, which operate on fixed schedule and hence are quite punctual [1]; and second the ability to combine the best attributes of the two modes to yield a more efficient and cost-effective overall movement.

Although rail-truck intermodal transportation has been used to move both regular freight and hazardous materials (hazmat), the volume of the latter has been steadily increasing over the past decade. For example, the Bureau of Transportation Statistics estimated that over 111 million tons of hazmat was shipped across the US intermodal transportation system in 2007, which represented 13.3% of the total hazmat shipment by ton-miles [2]. Such estimation was still on the conservative end, given that around 23% of the chemicals are moved on railroads [3] – some of which used rail intermodal since most clients do not have so called industrial-tracks for dedicated rail delivery, and the projection of the US chemical manufacturers association that the total volume of chemicals (including hazmat) shipped by 2020 will be over five-billion tons.Although IM has been an active research area within the intermodal transportation domain, the focus has been on regular freight. Despite the increasing significance of IM in carrying hazmat, it has not received commensurate attention of researchers in the hazmat domain [4].

In this paper, we developed an analytical framework for planning intermodal shipments of hazmat across an IM network, and posed the problem from the perspective of an intermodal railroad company that offers a door-to-door service. In an effort to address the interests of both governmental agencies and transport companies, we proposed a bi-objective optimization framework that capturedtransport risk and transport cost. The complexity of the problem structure, dictated by the characteristics of IM, necessitated the development of a tabu-search based solution methodology. Finally, in order to capture the punctuality feature of intermodal trains, route choices are driven by customer specified delivery times.The remainder of the paper is organized as follows. In §2 we present the bi-objective framework, followed by an outline of solution methodology in §3, and some managerial insights in §4, before concluding in §5.

II. Optimization Program

A typical rail-truck intermodal transport chain consists of: inbound drayage from shipper to origin-terminal; rail-haul between intermodal terminals; and, outbound drayage from destination terminals to the receiver. We assumed just-in-time movements of traffic and ignored the small possibility of congestion; existence of at least one feasible path; and, intermodal trains of the same speed operating on the same route arriving at the destination terminal around the same time.

SETS:Let I, J, K, and L be the set of shippers, origin-terminals, destination-terminals, receivers, respectively, with corresponding lower case as index. Furthermore, let P_{ij} (index: p) and Q_{kl} (index: q) indicate the set of drayage paths between i and j, and k and l, respectively. Finally, assume thatV_{jk} (index: *v*) and S^{v}_{jk} (index: *s*) indicate the set of intermodal trains between *j* and *k*, and service-legs for train *v*, respectively.

VARIABLES: Let X^{p}_{ijl} and $\overline{X}^{p}_{ijl}$,respectively, bethe number of hazmat and regular containers on path *p* of drayage *i*-*j* to meet demand at *l*; X^{q}_{ikl} and $\overline{X}^{q}_{ikl}$ be the number of hazmat

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and regular containers, respectively, on path q of drayage k-l from shipper i; X^{wv}_{ijkl} be the number of hazmat container on the w^{th} train of type v, and $\overline{X}^{v}_{ijkl}$ be the number of regular containers on train type v; and, N^{v}_{jk} is the number of trains of type v between j-k. In addition, there are indicator variables associated with each of the six flow variables. For example, $Y^{p}_{ijl}=1$ if either $X^{p}_{ijl}>0$ or $\overline{X}^{p}_{ijl}>0$, and 0 otherwise. Similar indicator variables are associated with other flow variables.

PARAMETERS: Let $\hat{C}^{p}_{ijl}$ be the cost of moving one container on path p of drayage i-j; $\hat{C}^{q}_{ikl}$ be the cost of moving one container on path q of drayage k-l; $\hat{C}^{v}_{jk}$ be the cost of moving one container on train of type v between j-k; FC^{v}_{jk} be the fixed cost of operating train v, between j-k; E^{p}_{ijl} and E^{q}_{ikl} be the population exposure risk from one hazmat container on path p of drayage i-j, and path q of drayage k-l, respectively; $E^{wv}_{jk}(\cdot)$ be the exposure risk due to hazmat containers on w^{th} train of type v. Furthermore, let t^{p}_{ij}, t^{q}_{kl}, and t^{v}_{jk}, respectively, be the time for inbound drayage, outbound drayage, and the rail-haul. Let DT_l be the delivery time specified by customer l, and U^{v}_{jk} be the capacity of train of type v. Finally, assume that the number of hazmat and regular containers demanded are D_{il} and $\overline{D}_{il}$, respectively.

(P)

Minimize

$$C(*)=\sum_{i,j,l,p}\hat{C}^{p}_{ij}(X^{p}_{ijl}+\overline{X}^{p}_{ijl})+\sum_{i,k,l,q}\hat{C}^{q}_{kl}(X^{q}_{ikl}+\overline{X}^{q}_{ikl})+\sum_{i,j,k,l,v}\hat{C}^{v}_{jk}(\sum_{w}X^{wv}_{ijkl}+X^{v}_{ijkl})+\sum_{j,k,v}FC^{v}_{jk}N^{v}_{jk}$$

$$R(*)=\sum_{i,j,l,p}E^{p}_{ijl}X^{p}_{ijl}+\sum_{i,k,l,q}E^{q}_{ikl}X^{q}_{ikl}+\sum_{j,k,v,w}E^{wv}_{jk}(\sum_{i,l}X^{wv}_{ijkl}) \qquad (1)$$

Subject to:

$$\sum_{p}X^{p}_{ijl}=\sum_{k,v,w}X^{wv}_{ijkl} \qquad \forall i,j,l$$

$$\sum_{p}\overline{X}^{p}_{ijl}=\sum_{k,v,w}\overline{X}^{v}_{ijkl} \qquad \forall i,j,l$$

$$\sum_{j,v,w}X^{wv}_{ijkl}=\sum_{q}X^{q}_{ikl} \qquad \forall i,k,l$$

$$\sum_{j,v}\overline{X}^{v}_{ijkl}=\sum_{q}\overline{X}^{q}_{ikl} \qquad \forall i,k,l \qquad (2)$$

$$\sum_{k,q}X^{q}_{ikl}=D_{il} \qquad \forall i,l$$

$$\sum_{k,q}\overline{X}^{q}_{ikl}=\overline{D}_{il} \qquad \forall i,l \qquad (3)$$

$$\sum_{i,l}(\sum_{w}X^{wv}_{ijkl}+\overline{X}^{v}_{ijkl})\le U^{v}_{jk}N^{v}_{jk} \qquad \forall v\in S_{jk}\cap V_{jk},j,k \qquad (4)$$

$$t^{p}_{ij}Y^{p}_{ijl}+t^{v}_{jk}Y^{v}_{ijkl}+t^{q}_{kl}Y^{q}_{ikl}\le DT_l \qquad \forall i,j,k,l,p,v,q \qquad (5)$$

$$MY^{p}_{ijl}\ge X^{p}_{ijl} \qquad \forall i,j,l,p$$

$$MY^{p}_{ijl}\ge \overline{X}^{p}_{ijl} \qquad \forall i,j,l,p$$

$$MY^{q}_{ikl}\ge X^{q}_{ikl} \qquad \forall i,k,l,q$$

$$MY^{q}_{ikl}\ge \overline{X}^{q}_{ikl} \qquad \forall i,k,l,q$$

$$MY^{v}_{ijkl}\ge X^{wv}_{ijkl} \qquad \forall i,j,k,l,w,v$$

$$MY^{v}_{ijl}\ge \overline{X}^{v}_{ijkl} \qquad \forall i,j,k,l,v \qquad (6)$$

Sign restriction constraints (7)

(P), a bi-criteria optimization model, with cost and risk objectives is represented in (1). The cost objective, i.e., *C(*)*, contains inbound and outbound drayage costs, rail-haul cost, and the fixed cost to operate different types of train services. The risk objective, i.e., *R(*)*, represents population exposure due to inbound and outbound drayage, and from each intermodal train of a specific type in the network. Note that the transport risk associated with a specific intermodal train type is a function of the number of hazmat containers in the train-consist, and hence we have an additional subscript w to keep track of each intermodal train. We briefly explain next, why the rail function for train (i.e., $E^{wv}_{jk}(\cdot)$) is non-linear.

In this paper, we made use of population exposure, i.e., the total number of people exposed to the possibility of an undesirable consequence, to represent transport risk. For example, according to the North American Emergency Response handbook [5], 800 meters around a fire that involves a chlorine tank, railcar or tank truck must be isolated and evacuated, and hence people within this specified distance are exposed to the risk of evacuation. The fixed bandwidth approach was first suggested by Batta and Chiu [6] and ReVelle et al. [7], and has been used by many authors since then [8]. In estimating the transport risk associated with IM shipments, we used the classical approach proposed above only for drayage since volume does not change for a standard truck. Such determination is non-trivial for intermodal trains, since we would need *a priori* information on both the number and location of hazmat containers on every train.In an effort to represent exposure risk as a function of hazmat volume

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being transported, we made use of Gaussian Dispersion Plume Model (GPM). GPM is a commonly used model for estimating the level of toxic material concentration as a function of the distance to the release source, release rate, wind speed and direction as well as elevation factors. If the concentration level at a point exceeded the threshold level specified by the regulatory agencies, then this point was considered exposed. It has been shown in hazmat literature that GPM can be used to model release effect from multiple sources (such as trains), and that the toxicity level increases much faster in the vicinity of the train as the number of railcars with hazardous cargo increases, i.e., the aggregate risk is non-linear [9]. This non-linearity complicated*a priori* determination of population exposure, since the risk function for the rail-haul could not be expressed in closed form until one knew the make-up of every intermodal train in the network. The absence of a closed form expression for rail-haul risk function also precluded using a standard optimization package to solve *(P)*, and necessitated the development of a specific solution methodology.

Constraint (2) represents the transshipment function being performed by the intermodal terminals, while accounting for different types of intermodal train services in the network. It should be noted that transshipment constraints for hazmat and regular freight have to be distinguished in order to track them separately. Constraint (3) ensures that each receiver's hazmat and regular freight demands are satisfied. Constraint (4) states that the number of intermodal train of a specific type will be determined by the total number of containers to be moved between two consecutive terminals (i.e., on a train service leg). Constraint (5) ensures that all shipments arrive at the customer location by the specified delivery-times. Constraint (6) captures activation of indicator variables associated with different links, and this information is used in (5) to evaluate the feasibility of including that link in forming an intermodal chain. Finally, the sign restrictions constraints are contained in (7), wherein flow variables and the number of trains of different types are integers, while the indicator variables are binary.

III. Solution Methodology

In this section, we describe a way to optimally solve the shipment of regular containers, and then outline a tabu-search method for routing hazmat containers.

A. Regular Containers

In order to ship all the regular containers, $\overline{X}(i,l,t)$, requested from shipper *i* to receiver *l* before time *t*, we had to search for shortest paths (cheapest) from *i* to *l* in the following network $G=(V,A,z)$. Each arc $(x,y)\in A$ represented a possible transportation option from *x* to *y*, and is in the set $(I\times J)\cup(J\times K)\cup(K\times L)$. Since drayage was performed by trucks, for any given vertices in *x* and *y* in $(I\times J)\cup(K\times L)$, there was only one associated arc *(x, y)* even if several trucks traveled from *x*to *y* (i.e., it represented the shortest path in *G*). In contrast, transportation on the arcs of $(J\times K)$ was performed by trucks, and hence if there were several trains going from a vertex *x* in *J* to a vertex *y* in *K*, then each train was represented by a different arc. The weight *z(x, y)* associated with arc *(x, y)* was the encountered cost if used arc *(x, y)*. Note that the risk associated with regular containers was zero.

Using the famous Dijkstra's algorithm, each was assigned to the shortest path from *i* to *l*. If a shipment was late, we replaced the rail-haul with the next faster train which in turn reduced the travel time but increased the cost. It is important that since drayage was already being performed using the quickest (or shortest) link, the travel time could not be reduced by moving to any other drayage link. Note that although any infeasibility could have been handled by attaching a penalty function, we assumed that at least one feasible intermodal route existed between each shipper-receiver pair. The above described process was done once and for all in our general heuristic, and needed only a small amount of computing time (a few seconds).

B. Hazmat Containers

As indicated earlier, the rail-haul objective does not have a generic closed form expression, and is non-linear. This is because population exposure around each rail-link is estimated by multiplying the length of the link, the threshold distance for the undesirable consequence of concern, and the population density in the vicinity. Given the complexity associated with rail-haul risk objective, routing hazmat containers using exact method would be both inefficient and cumbersome, especially for large scale problem instances.

(P) consists of a large number of constraints but fewer variables, and hence a local search heuristic may be appropriate. We chose tabu search [10], over other local search methods (such as simulated annealing, variable neighborhood search) due to its demonstrated success on problems involving dispatching *n* objects into *k* sets within a constrained setting [11, 12]. In the interest of space, we briefly outline the different steps of tabu search adopted for our problem instance.

<u>Pre-processing:</u> We adaptedtabu search for our problem instance as follows. Let $X(i,l,t)$ be the set of hazmat containers to be moved. We generated a set of feasible arcs $F(i,l,t)$ for each $X(i,l,t)$. This ensured that a hazmat container would not be assigned to an arc *(j, k)* that violated the specified delivery-time.

<u>Solution Evaluation:</u>Although hazmat transport risk accrued all along the transportation corridor, the non-linear (and unknown) part occurred only on the rail-haul links. In order to ship hazmat containers at minimum cost and risk, we mainly had to find their best assignments to the arcs in set $J\times K$. Let ***s*** be an assignment solution of all the hazmat containers to the arcs in set $J\times K$. If and only if ***s*** was completely known, we could compute the objective function $f(s)=\alpha C(s)+(1-\alpha)R(s)$, where *C(s)*was the cost

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associated with the assignment solution *s*, and α was a parameter that lied within [0, 1]. Given a solution *s*, we considered the network $G = (V, A, w)$, where *V, A* were defined as above, and *w* was the weight *w(x, y)* associated with arc *(x, y)*. Hence, the length of the path was the sum of its associated weights.

Neighborhood and Tabu-Tenure: In order to generate a neighbor solution *s'* from *s*, we proposed to change the assignment of all the hazmat containers from , while maintaining the feasibility of the solution. More precisely, we moved hazmat containers from arc *(j, k)* to an arc *(j', k')* of . At each iteration, we always chose the best non-tabu feasible neighbor solution *s'*. A tabu move was allowed only if it lead to a solution better than the best one encountered.

Neighbor solutions can be generated quickly, because of the incremental computation and an efficient tabu tenure management scheme. Let *s* be the current solution and *s"* a candidate neighbor solution obtained as a result of move from *s*. To evaluate *s"* quickly, we just computed the variation (i.e., *Delta(f)*) as a result of the move. If *Delta(f) < 0*, the move was improving, and was the difference between: the additional cost and risk of moving to a new arc; and, the savings as a result of leaving the current arc.

Stopping Conditions: The algorithm stopped when a given amount of CPU time was reached. We provide further details in the next section.

IV. Computational Experiments

Fig. 1 depicts the 37 shippers/receivers located in the mid-west, north-east, and south-east regions of the United States. These locations, selected based on the existing intermodal network in the region, are represented via a geographical information system (GIS) model using ArcView [13]. A total of 20 intermodal terminals and 62 different types of intermodal train services were available to the shippers/ receivers in the three regions. Note that two types of intermodal train services –*regular* and *priority* –were operating between each terminal pair, and that the latter was 25% faster than the former. We use hypothetical demand data which were randomly generated utilizing the fuel oil consumption figures as compiled by the Department of Energy. In our data set, a total of 22190 intermodal containers, including 10965 with hazardous cargo had to be moved. Finally, without loss of generality, we also assumed that the lead-time to satisfy demand at each shipper was 48 hours.

The solution methodology was coded in Python, and all numerical experiments were performed on Apple, running Mac OS x 10.5.6 and Python 2.6.1 [14]. Before applying tabu search, we tuned the "percentage of neighboring solutions considered" and "time limit", and after numerous computational runs concluded that 1% and 15 minutes, respectively, were most appropriate.

A. Solution

Two of the common techniques, as evidenced through published works, for solving multi-objective models are pre-

Fig. 1. Shippers and Receivers

emptive optimization and weighted sums [15, 16]. Although we attached equal weights to the two objectives to solve the realistic problem instance (hereafter, referred to as the *Base-Case*), we also report on a parametric analysis performed by attaching different weights to the two objectives.

After 13682 iterations and 15 minutes of CPU time, the *Base-Case* solution entailed exposing approximately 8.9 million individuals and spending around $72.7 million in order to meet demand. A significant portion of both cost and risk, 80% and 94% respectively, accrued from drayage operations, which should be of interest to decision-makers. A total of 170 *regular* and 49 *priority* trains were used to meet demand. Of these, a total of fifty-seven hazmat unit-trains, including twenty-five of the priority type, were formed. Although hazmat unit-trains lower network risk and hence may be desirable, such formation may not be favored by the regulators and risk-averse decision makers.

The decoded solution also indicated that Philadelphia, Indianapolis and Atlanta were the three busiest yards, which in turn could be explained by the fact that twelve of the 31 train services originate at these yards, and another 18 transit them. Two observations can be made in this regard: first, these terminals were the major access points for the three regions, which can be important for designing intermodal service networks; second, the expected risk at these sites would be the highest, which was a good surrogate measure to justify installation of commensurate emergency response systems.

Given the cost and risk stemming from highway part of the chain, it was clear that drayage attributes were extremely important in this problem instance. While the regular containers took the shortest path to/from the terminals, this was not the case for hazmat containers. It was noticed that most of the hazmat containers did not take the shortest path since these were often the riskiest. For shipments dispatched over the shortest path, the travel-time on less risky but longer paths resulted in infeasible intermodal chains. It was reasonable to conclude that given enough time for drayage, hazmat containers could take longer but less risky paths without violating the specified delivery time.

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A. Managerial Insights

In an effort to get managerial insights, we first analyze the insights from risk-cost tradeoff; and then briefly comment on the captive areas for terminals and solution sensitivity to perturbation in delivery-time.

Risk-cost tradeoff:First, we report on a parametric analysis on the problem instance by varying the weights associated with the cost and risk objectives. Note that both of these weights are 0.5 in the *Base-Case*. Each point in Fig.2 represents a non-dominated solution, with the *Min Cost* and the *Min Risk* constituting the two extremes. The*Min Cost* solution was 2% less expensive than the *Base-Case* solution, but 65% more risky. The increment in risk was primarily stemming from forcing drayage operations through shorter but more risky paths. On the other hand the *Min Risk* solution was 6.4% more expensive, thanks to a higher number of *priority* trains. It should be noted that the use of faster trains had enabled taking longer but less risky paths, which in turn translated into a 17.2% risk reduction. In addition it was noticed that the increased traffic, through Atlanta and Indianapolis, was handled by eleven additional *priority* trains with origin/destination at the two intermodal terminals.

One can see that the *Min Cost* solution entailed a cost of around $71.3 million and exposed 14.9 million people, whereas the cost of the *Min Risk* solution was $77.3 million and the exposure was 7.44 million people. By spending an extra $6 million, it was possible to halve the population exposure risk. This may be a worthwhile trade-off for the regulators to pursue. Perhaps a more important observation was the significant increase in population exposure risk when the weight attached to the risk coefficient was decreased from 10% to 0% (i.e., from *A* to *Min Cost*). This weight allocation resulted in a saving of around $175K but increased exposure risk by 3 million people, which implied that every saved dollar exposes 17.4 additional individuals to hazmat risk.

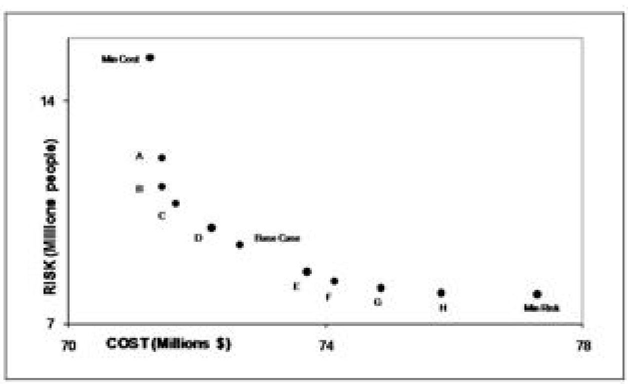

Fig. 2. Weight based solutions

Captive areas for terminals: Changes in container routing were noticed in all problem instances, and hence it was possible to conclude –that delivery time permitting, the choice of terminal for routing traffic depended on the objective function being emphasized.

Variation in delivery-time: Reduction in delivery time will almost always necessitate more premium trains, whereas increase will shift more traffic onto regular trains. The consequent impact on drayage could result in higher or lower risk, depending on the problem setting and alternate routing options.

Conclusion

In this paper, we presented an optimization framework for planning rail-truck intermodal shipments when both shippers and receivers have access to a number of intermodal terminals. It is important that route selection, and hence the formation of feasible intermodal chain, be driven by customer specified delivery-times.Complexity of rail-truck intermodal transportation system and the intent to exploit the problem structure motivated the development of a tabu-search based solution methodology, which was applied to realistic size problem instances based in eastern U.S.

Through extensive computational experiments, we can make four important observations. *First*, drayage is responsible for a significant portion of intermodal transport risk, and every effort must be made to reduce it. *Second*, scheduling direct intermodal trains or using hazmat unit-train can result in the reduction of rail-haul transport risk. *Third*, the number of different types of trains depends on the objective being emphasized. *Fourth*, resulting traffic flow can help identify potential bottlenecks, and facilitate planning commensurate emergency response systems. The aforementioned insights can be used by regulators to both devise policy instruments and also negotiate with the other important stakeholder (i.e., transportation companies) to ensure safe and secure movement of intermodal hazmat shipments.

Other directions for future research include, studying congestion in the IM system; comparing the performance of intermodal transportation with road and rail shipments from a risk-cost perspective; and investigating the assignment of containers to flat railcars and makeup of intermodal train services when hazardous cargo is involved.

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